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"Vortex Boundary-Layer Interactions"

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Summary

Full-time work has now been in progress for 18 months (the post-doctoral research assistant, Dr A.D. Cutler, having taken up his post on 1 October 1984) and is essentially on schedule. The proposed parametric studies to identify a suitable vortex generator have been completed, and we have nearly completed data acquisition in the first chosen configuration, in which a longitudinal vortex pair generated by an isolated delta wing starts to merge with a turbulent boundary layer on a flat plate fairly close to the leading edge. Our earlier work on a delta-wing/flat-plate combination, consisting of flow visualization and some hot-wire data, has now been written up for presentation at an AIAA meeting in Atlanta during May (paper AIAA-86-1071, ~~attached as Appendix A)~~. Another version of this paper has been submitted for publication in the Journal of Aircraft. Part of the time in the last six months has been taken up with the implemention of a faster data-logging system. Data taking and primary analysis for the present configuration will be completed shortly, and measurements in a second configuration with the delta-wing vortices higher above the test plate will follow, concurrently with further data analysis.

Present Position

In the previous progress report, covering the half-year March-August 1985, sample hot-wire measurements taken with a computer-controlled traverse gear and data-logging system were presented. Data taking and analysis have continued, and sample results for a another cross-stream plane are presented in this report to indicate the extent and precision of the measurements. The available data include all mean velocity components, all six second-order mean products of turbulent fluctuations and all ten third-order mean products: the intention is to cover enough cross-stream planes to allow several streamwise checks on calculations starting at the upstream-most plane. Sufficient data points in a given plane will be acquired to allow differentiation of the data in the y- or z- directions and at least one pair of planes will be sufficiently close in the streamwise direction to allow reliable differention of the data with respect to x: this will allow the evaluation of, for example, the terms in the turbulent kinetic energy equation.

Figure 1 shows the test rig, in which the trailing vortices from a delta wing pass over the top of a flat plate while the non-rolled-up part of the wake passes below the plate. The flow is quite accurately symmetrical about the central plane and interaction between the two vortices is small, although they induce strong lateral divergence of the boundary layer between them.

Results given in previous progress reports were acquired with an IBM-PC clone microcomputer and a Tecmar Inc. "LabMaster" A/D conversion system. Recently a faster computer system, using a true 16-bit bus with an Intel 8086 CPU and 8087 arithmetic chip, has become available on completion of an AFOSR-supported project on impinging jets. After a six-month delay in delivery of a Dual Computer Inc. A/D board, the system has been adapted for the present experiment and has greatly increased the rate of data acquisition. This increase in data acquisition rate was essential in order to obtain the density of data required for the above mentioned differentiations of data, in a reasonable amount of time and with the necessary accuracy.

Figures 2-6 shows contour or vector plots of quantities derived from hot-wire data acquired with the new data-logging system in a plane at x=54.25 inches. Data for y>6 in. are avaiable but the scale of the attached plots is already too small to distinguish contours in the core. These are hand-drawn contours through values, at each label position, interpolated from the traverse readings: to produce final plots, the hand-drawn contours will be re-digitised and then smoothed by a computer routine.

At this station, x=54.25 in., the extraction of fluid from the boundary layer by the vortex, visible in the results at x=34.25 in. (figure 7), has become very pronounced. Figure 2 shows the mean U-component velocity, figure 3 the mean V- and W- component velocities, figure 4 the x-component vorticity ($\partial W/\partial y-\partial V/\partial z$) and figure 5 the turbulent kinetic energy $(1/2)\overline{q^2}$, where $\overline{q^2} = \overline{u^2} + \overline{v^2} + \overline{w^2}$ instantaneously or in the mean. Figure 6 shows the vector representing the "turbulent transport velocity" of turbulent kinetic energy in the cross-stream (y-z) plane. "Transport velocity" is simply the rate of flux of the transported quantity divided by the quantity itself, so the components of the vector shown in Figure 6 are $(\overline{q^2v}/\overline{q^2}, \overline{q^2w}/\overline{q^2})$. (The contribution of pressure fluctuations to turbulent transport of turbulent kinetic energy has been omitted: it is usually assumed to be small and is certainly unmeasurable.) Comparison of figures 5 and 6 shows that the transport velocity is generally, but not always, away from regions of high turbulent kinetic energy - "gradient diffusion", represented by an eddy viscosity, is a qualitative guide but not a reliable quantitative model. Considering that the transport-velocity vector is defined in terms of no less than nine measured quantities ($\overline{q^2 v}$ and $\overline{q^2 w}$ each being the sum of three triple products which are notoriously hard to measure) we feel that the smooth distributions shown in Figure 6 imply a high order of consistency in our data (absolute accuracy being limited by the response of the hot wire anemometer). Plots of simpler quantities are equally consistent. Finally, Figure 7 shows the turbulent kinetic energy at the plane at x=34.25 inches, obtained with the old data-logging system: comparison with Figure 5 shows the streamwise development of this quantity, and, notably, the clockwise rotation of the "tongue" of boundary layer fluid around the vortex.

The results and conclusions to date are discussed in detail in AIAA-86-1071 attached as Appendix A. Detailed measurements in the vortex-pair wake of the delta wing have revealed a more complicated structure than is implied by quasi-inviscid models of the "conical" flow over the delta wing itself. Briefly, the non-rolled-up part of the wake, forming a spiral around each vortex core, carries a significant amount of turbulent energy and (partially negative) circulation, while radial mixing in the true core of the vortex is so small that smoke reaches the vortex axis only if introduced very near the leading edge of the delta wing. Smoke actually introduced into the core is not centrifuged out, and heated fluid outside the core is not centrifuged inwards. Thus the widely-credited argument that heavy contaminants such as smoke or dye are expelled from a vortex core by "centrifugal force" is not correct; they are simply never diffused into the core, and, even on the scale of aircraft trailing vortices or tornados, the core remains non-turbulent because of the stabilizing positive-outward gradient of angular momentum. High levels of Reynolds stress are measured in the core region in the present experiment (Figures 5 to 7), but these can be attributed in large part to a small amplitude, random wandering of the vortex core which is jet-like in its mean u-component velocity.

The vortices have a very dramatic effect on the development of the boundary layer developing on the flat plate. Strong crossflow is induced in the boundary layer underneath each vortex and, as a consequence of the no-slip condition (w=0 at the plate), the layer contains longitudinal vorticity which is opposite in sign to that in the vortex above. After passing under the vortex the boundary-layer fluid breaks away from the surface as a "tongue" of turbulent fluid at a separation point and is subsequently entrained into the vortex. The full understanding of the behaviour of the turbulence in the strongly diverging boundary-layer underneath the vortex pair and in the tongue, which is a major objective of this project, awaits further data acquisition and analysis.

Because of the impingement of the delta-wing downwash on the flat plate, part of each spiral vortex sheet ends up near the centre plane in our rig, complicating the behaviour of the plate boundary layer between the vortices. This effect would be less noticeable for a plate further downstream of the delta wing, but our rig is typical of close-coupled canard or double-delta aircraft, which ar:e of some practical interest.

Future Plans

Although the data acquisition system provides immediate tabulations, on floppy disc, of all mean velocity components and second- and third-order products of velocity fluctuations, we expect that a large amount of contract time will be taken up by further data analysis and plotting of derived quantities in human-readable form. We plan to evaluate and plot correlation coefficients, eddy viscosities, x-component vorticity and all the terms in the momentum, turbulent kinetic energy and x-component vorticity equations (except the terms which contain the fluctuating component of pressure). We also intend to make a complete set of measurements in another configuration, in which the delta-wing vortices remain clear of the test plate nearly until the end of the test section. Thus the flow over most of the plate will be a true boundary layer, with strong crossflow induced by the nearby, but unmerged, vortices. This configuration is of course more representative of canard aircraft at high angle of attack, and should provide a demanding test case for "boundary layer" calculation methods (i.e. those claimed to be capable of predicting 3D flows with large crossflow, but not true imbedded vortex flows with fully elliptic behavior in the crossflow plane).

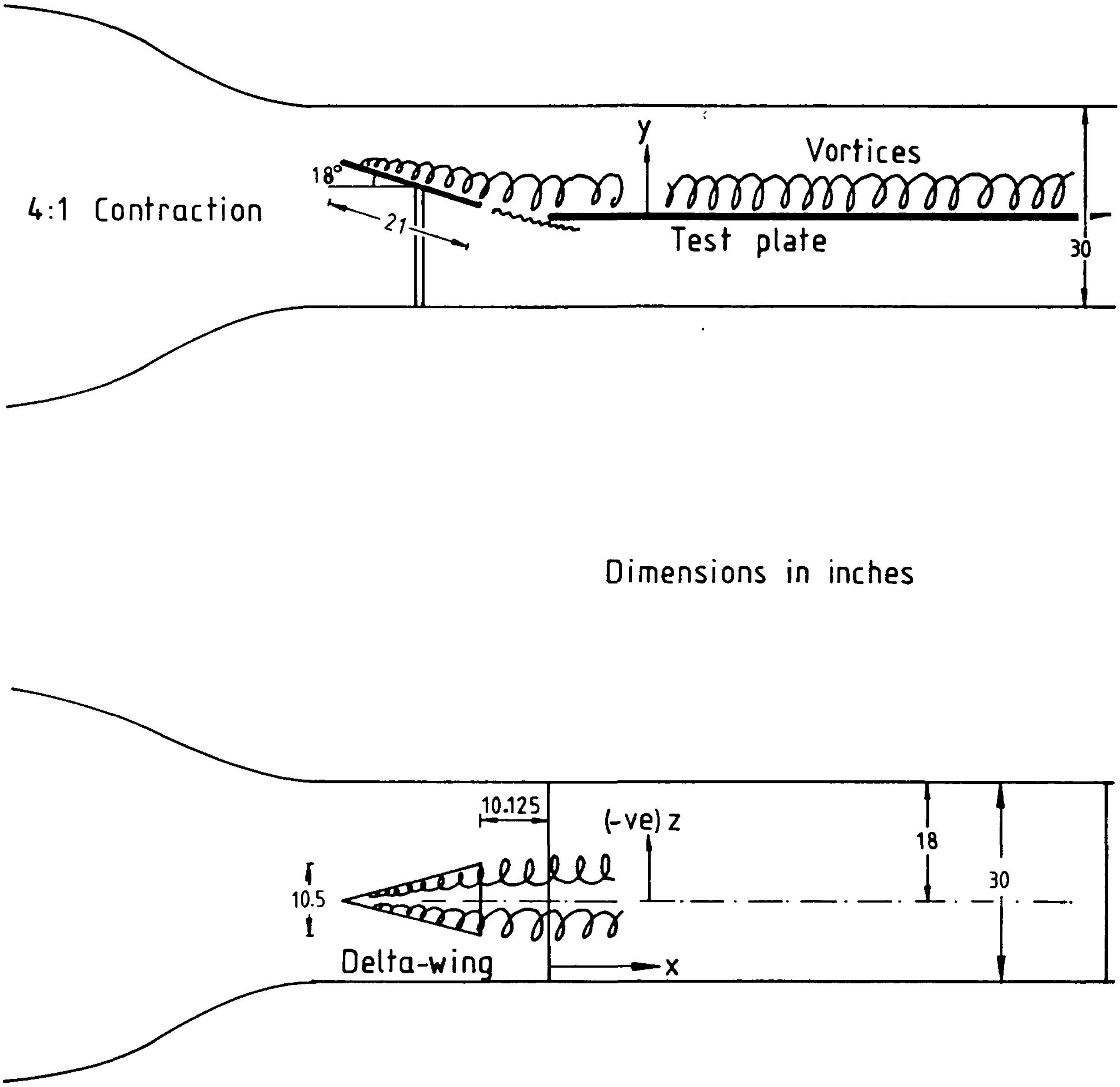
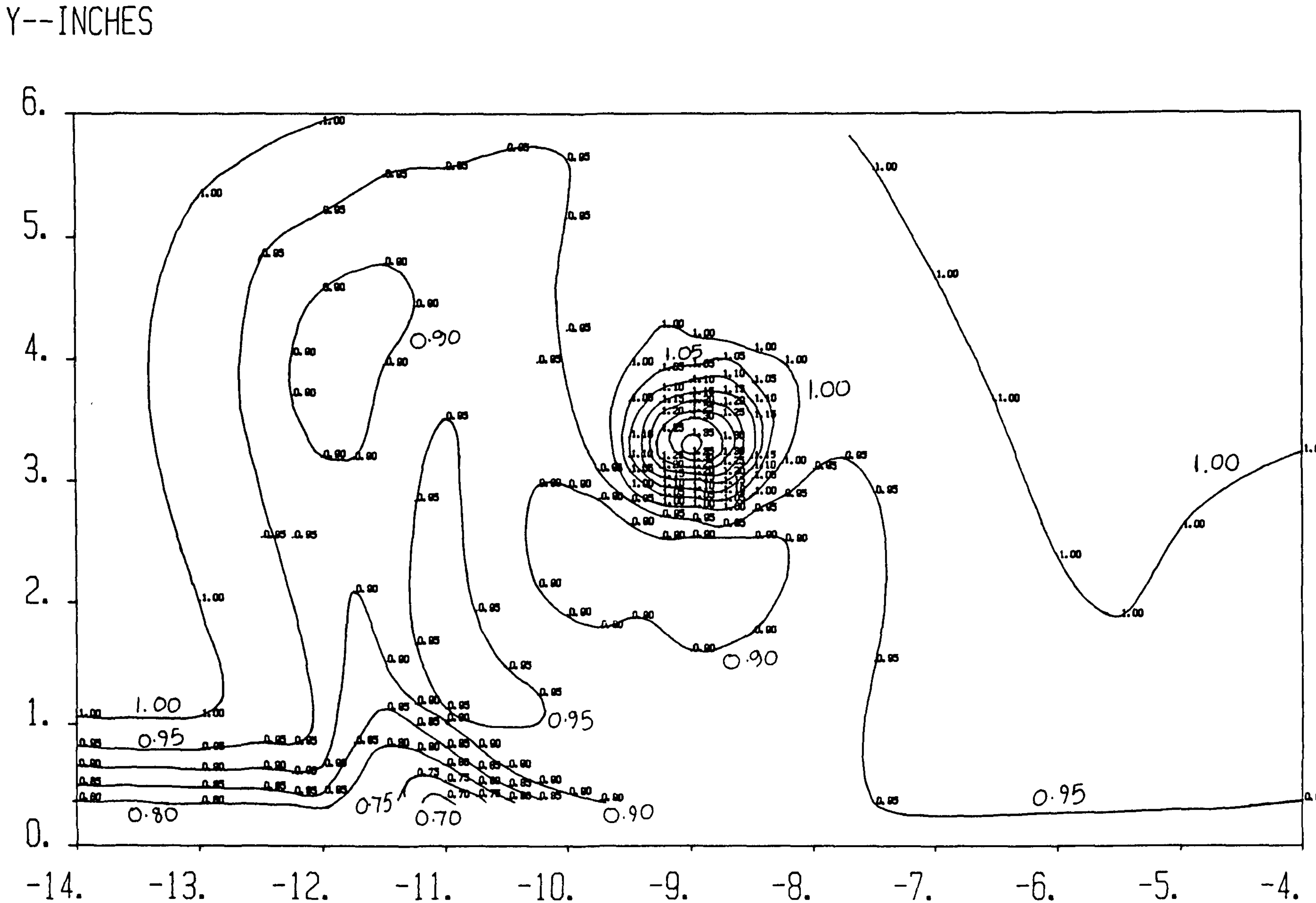


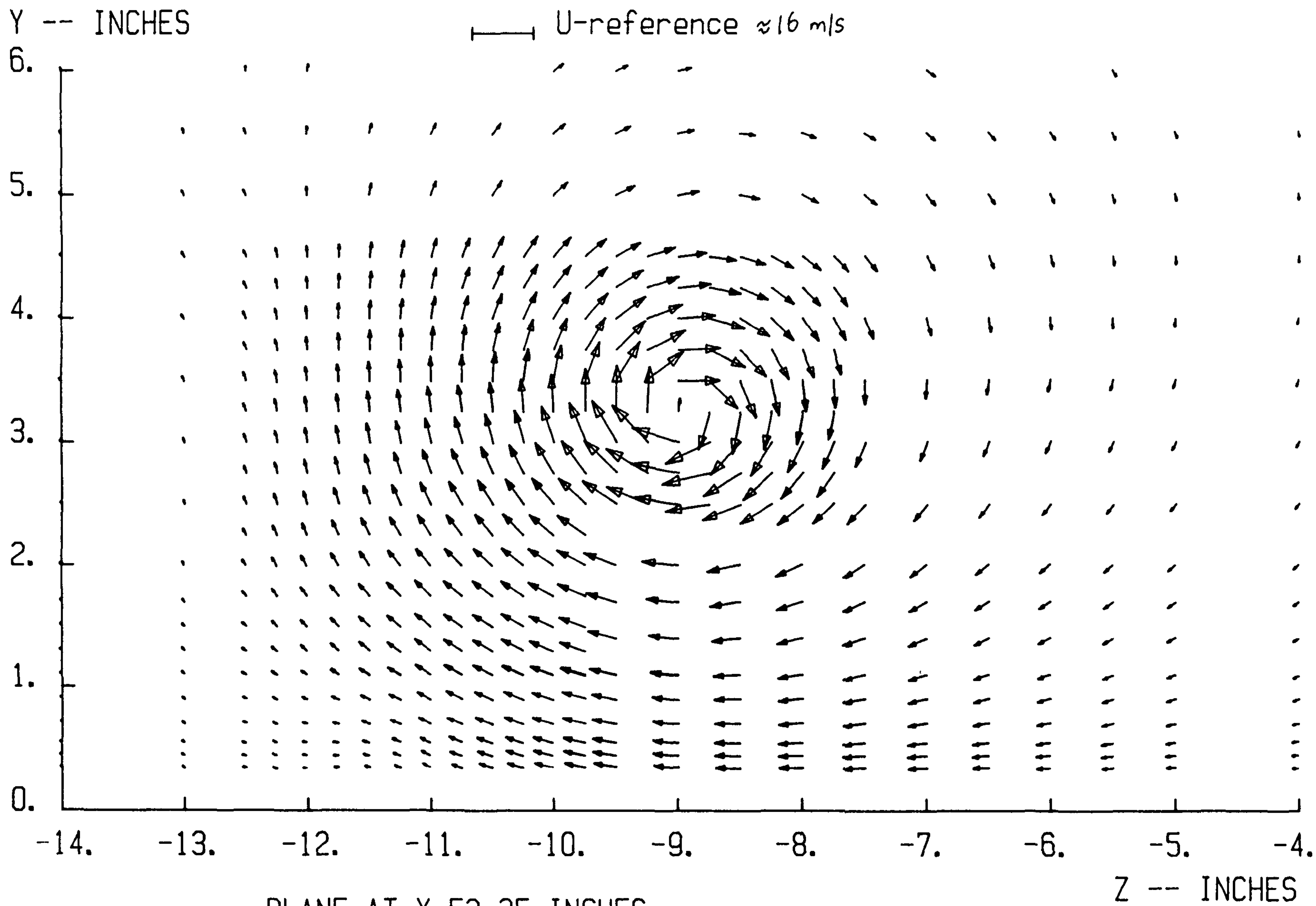
Figure 1 Test Rig



PLANE AT X=52.25 INCHES

CONTOURS OF MEAN U-COMPONENT VELOCITY = U/U_{ref} [$U_{ref} \approx 16$ m/s]

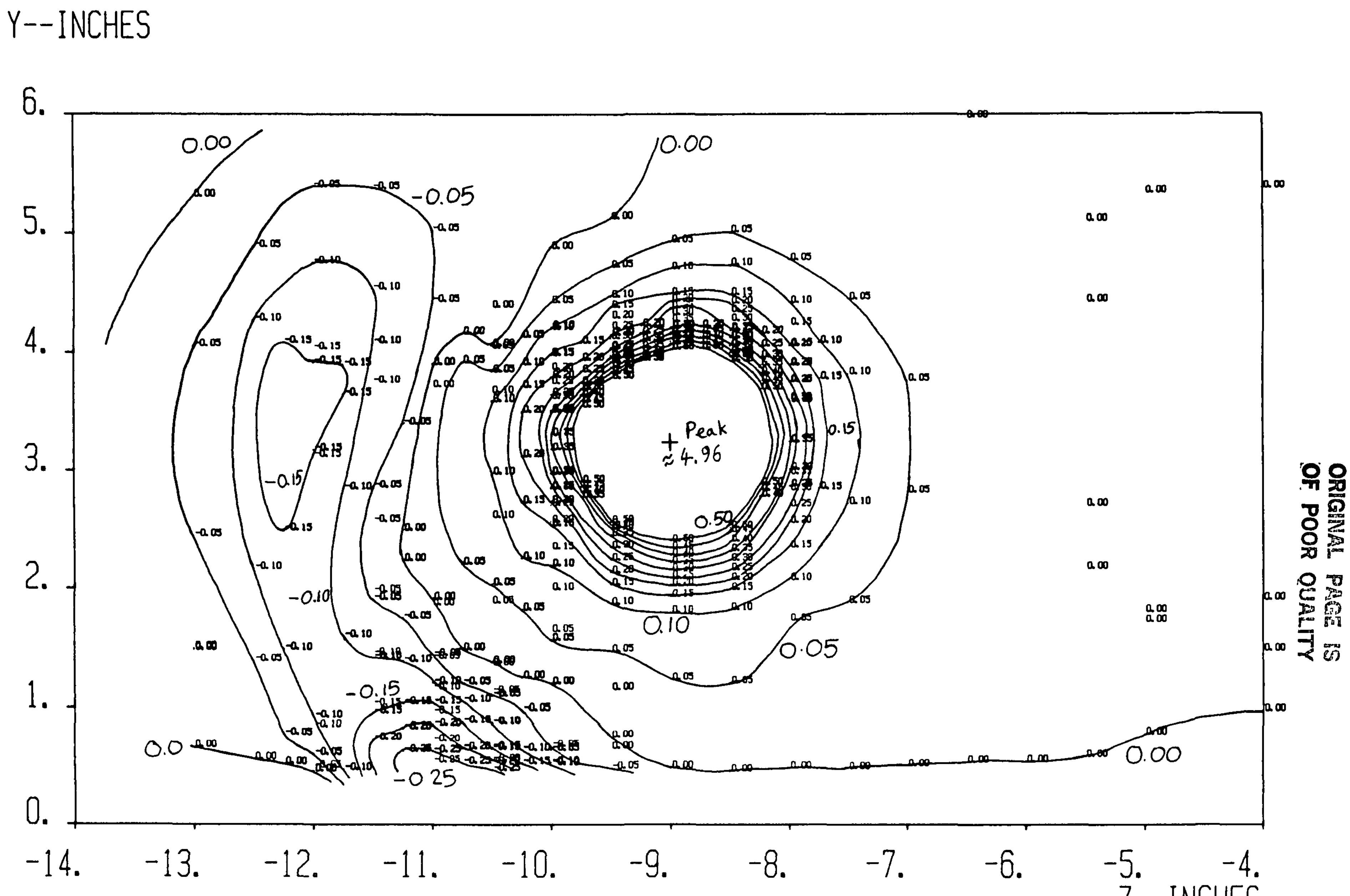
Figure 2



PLANE AT X=52.25 INCHES

SECONDARY FLOW MEAN VELOCITY V,W

Figure 3



PLANE AT X=52.25 INCHES

CONTOURS OF X-COMPONENT VORTICITY $\equiv \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right) / U_{ref}$ [$U_{ref} \approx 16.0$ m/s]

Figure 4

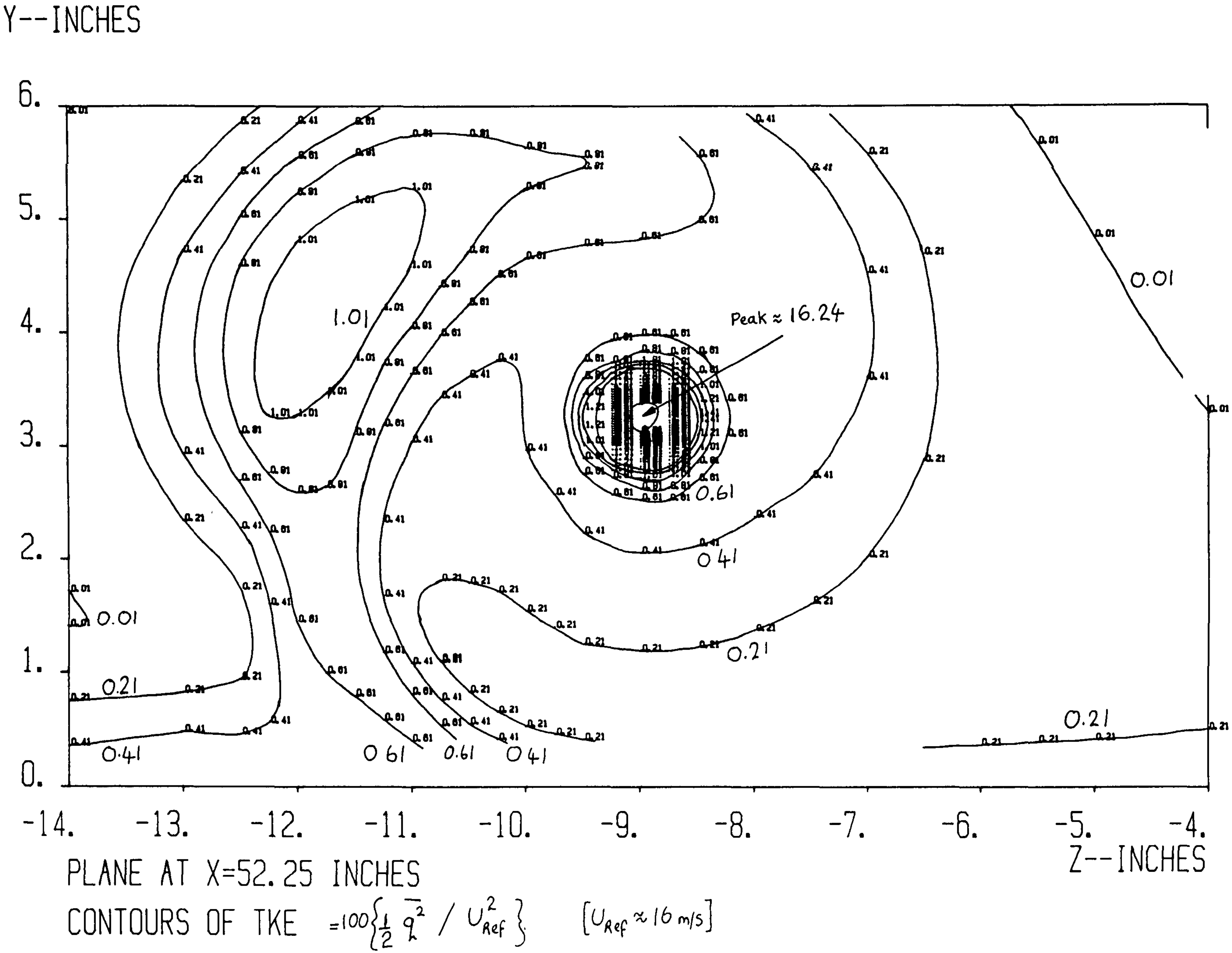
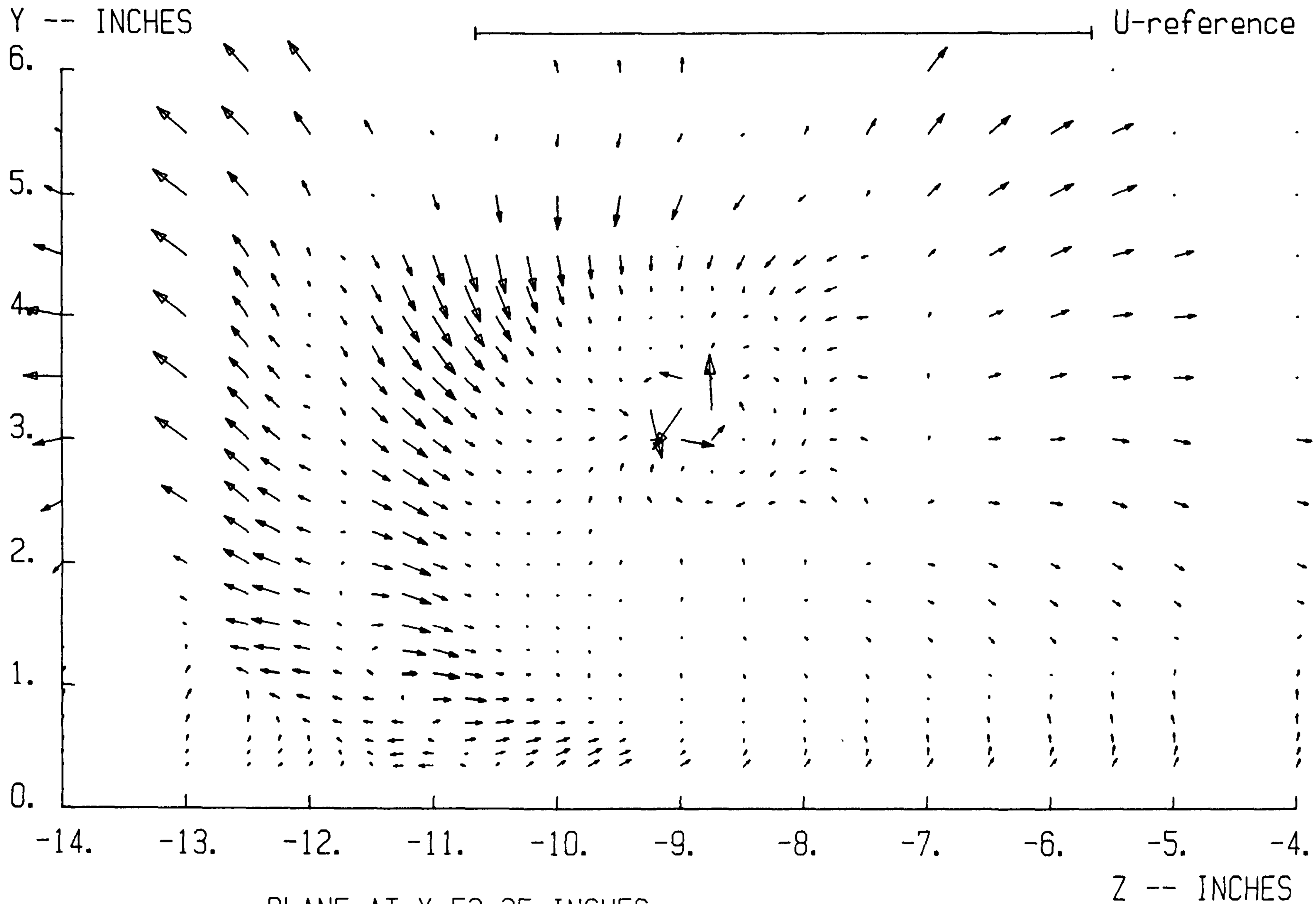


Figure 5 (in some hard copies this is a transparency to overlay Figure 6)



PLANE AT X=52.25 INCHES.
Y-Z PLANE TKE DIFFUSION VELOCITY

Figure 6

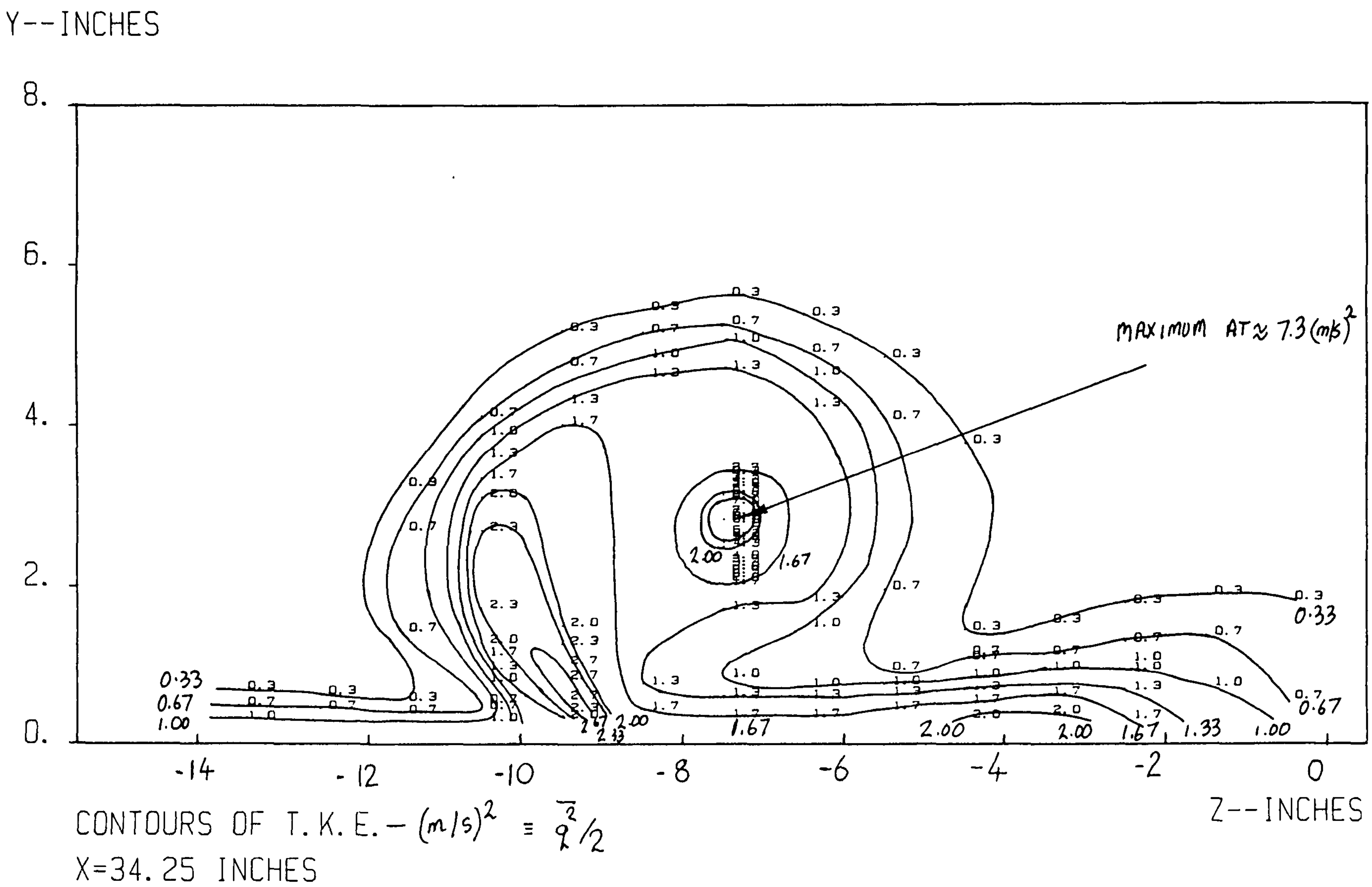


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Figure 7